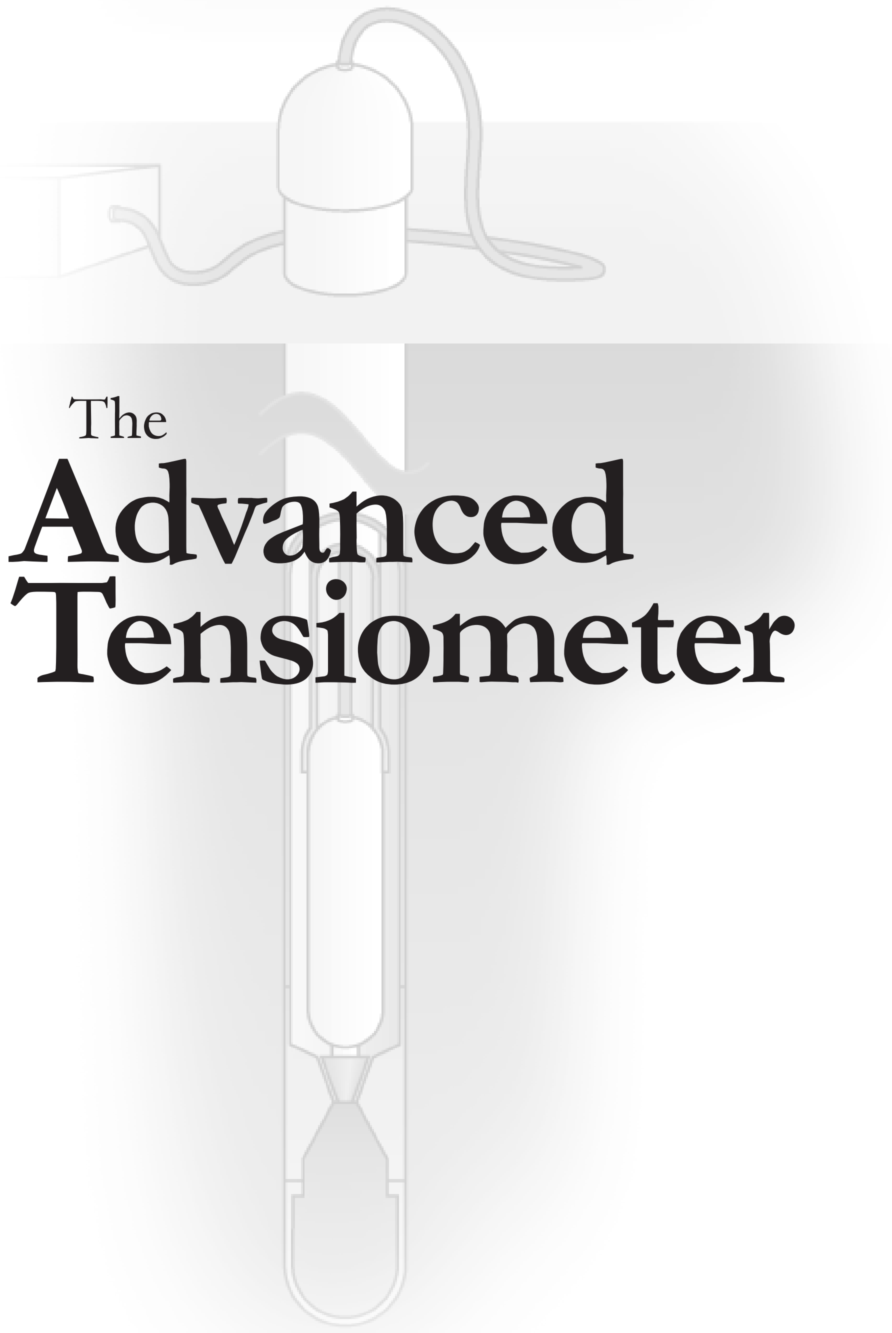
Idaho National Engineering and Environmental Laboratory

The Advanced Tensiometer



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Introduction

This document contains three papers on advanced and portable tensiometers. The first paper describes the construction and use of the advanced tensiometer and compares it to existing conventional tensiometers. The second paper presents data from two sites (0-30 m depth) instrumented with advanced tensiometers in sediment and basalt and suggests that deep vadose zones will generally be within the tensiometeric (0-1000 cm) range. The third paper describes the construction and uses of the portable tensiometer, a portable version of the advanced tensiometer.

Dr. James Sisson and Joel Hubbell are recipients of the 1997 Research and Development 100 Award for the Advanced Tensiometer.

James “Buck” Sisson is a Consulting Scientist in the Geosciences Department. He has worked on research relating to soil physics for over 20 years. He taught Soil physics at Kansas State University for 7 years and was a senior Soil Physicist at Rockwell Hanford Operations for 5 years. He has been granted 5 patents and has 2 patents pending for vadose zone instrumentation.

Joel Hubbell is an Advisory Scientist in the Geosciences Department of Bechtel BWXT Idaho, LLC. He has over 13 years experience at the Idaho National Engineering and Environmental Laboratory working on vadose (unsaturated) zone and ground water projects. He has designed and developed an array of vadose and groundwater monitoring instruments. He has been granted 4 patents and has five patents pending relating to vadose zone/ground water monitoring and sampling technologies. He has submitted nearly 20 invention disclosures in the past 9 years, and authored over 20 internal and external documents.

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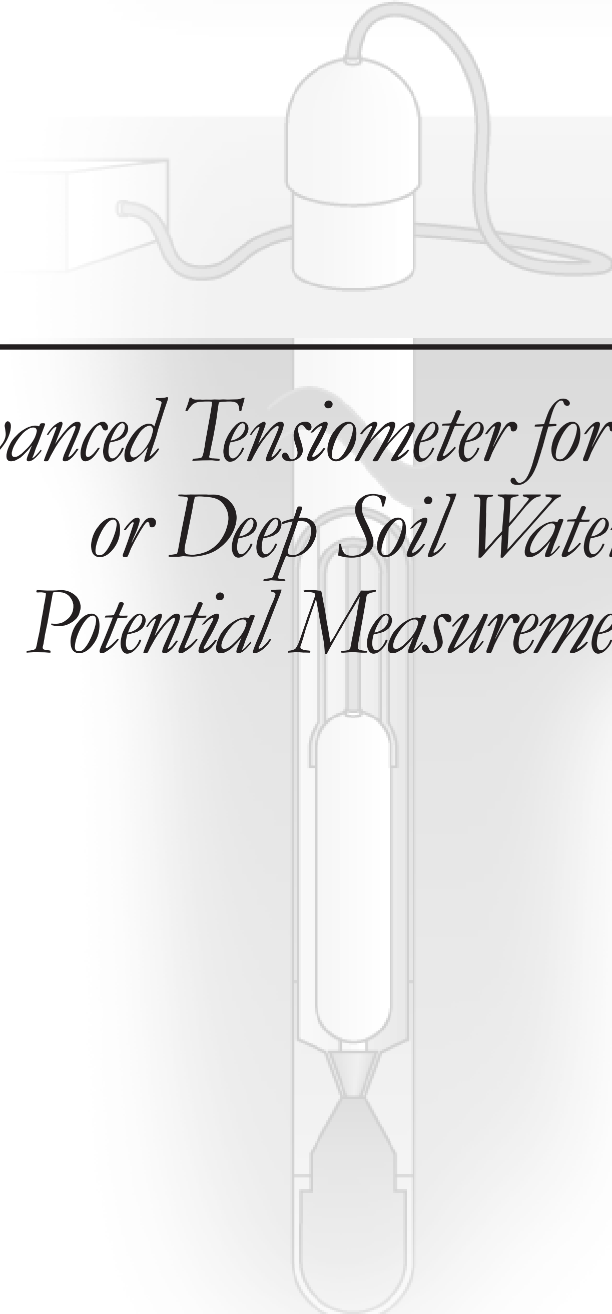

Advanced Tensiometer for Shallow or Deep Soil Water Potential Measurements

Part 1

Advanced Tensiometer for Shallow or Deep Soil Water Potential Measurements

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ABSTRACT

Tensiometers are required for measuring soil water potential at depths exceeding several meters to quantify the direction and rate of soil water movement. This paper describes a permanently installed tensiometer (advanced tensiometer) to measure soil water potentials at any depth below land surface. The advanced tensiometer was designed with a removable pressure transducer to allow for field calibration and servicing. The advanced tensiometer has two parts, a permanently installed outer tensiometer assembly and a removable transducer assembly. The permanently installed portion has a porous cup, an adapter containing a reservoir of water, and an outer guide pipe that extends to land surface. The removable electronic pressure transducer assembly has a stopper on the bottom, a connector to attach the stopper to a pressure transducer and an inner guide tube to raise and lower the assembly. The transducer assembly is lowered into the outer tensiometer assembly until the stopper connects and seals into the permanently installed adapter. This configuration of the advanced tensiometer allows it to be installed at any depth. Advanced tensiometers were operated at depths of 2 to 4.8 meters for periods exceeding 3 months with no maintenance. The nearly constant temperature condition in boreholes provided for stable, long-term water potential values and reduced field maintenance.

INTRODUCTION

Tensiometers are used to obtain measurements of soil water potential between 0 and about -1000 cm (Gardner et al. 1922; Richards 1931; Cassel and Klute 1986). Tensiometers work in the soil water potential range with the highest unsaturated hydraulic conductivities and thus the greatest potential for rapid water movement. Multiple tensiometers in a profile are used to calculate hydraulic gradients to determine the direction of water movement and to estimate water flux using unsaturated hydraulic conductivity (Morrison 1983). The movement of water in the unsaturated zone is important for engineering investigations (Wilson et al. 1995), hazardous-waste site monitoring (Healy et al. 1984; Everett et al. 1984), recharge studies (Sophocleous and Perry 1985), and irrigation management practices (Cassel and Bauer 1976; Hagan et al. 1967). Numerous configurations of tensiometers have been built since their conception (Gardner et al. 1922; Richards 1931; Morrison 1983; Cassel and Klute 1986; EPA 1993; Hubbell and Sisson 1996). Tensiometers are comprised of three components: a porous cup or plate, a pressure sensor, and a reservoir filled with water connecting the porous cup to the pressure sensor.

Conventional tensiometers are equipped with the pressure sensor mounted above land surface limiting installations to a few meters below land surface. The length of the water column adds to the vacuum in conventional tensiometers, thereby reducing the effective range by the length of the water column. Tensiometers have been constructed with a pressure transducer buried at or near the sensing tip to circumvent this depth limitation and allow automated data collection (Klute and Peters 1962; Strebel et al. 1973; Williams 1978; Trotter 1984; Nyhan and Drennon 1990). However, this technique does not provide easy access for field calibration, replacement or maintenance of the transducer. An air filled tensiometer was proposed to eliminate the depth limitations by Faybishenko (1986) by partially filling a lysimeter (tensiometer) with fluid and recording soil water potential using the fill tubes at land surface. These instruments have a delayed response to water potential changes and require two pressure measurements to obtain soil water potential measurements. Tokunaga (1992) and Tokunaga and Salve (1994) presented test results from air filled tensiometers. Hubbell and Sisson (1996) presented a technique to obtain soil water potential measurements using a portable tensiometer. This instrument can be installed at nearly any depth and operated for extended time periods without field maintenance. The portable tensiometer has a slower response time than a conventional tensiometer due to the small contact area between the porous cup and the sediment and it must be removed to land surface to service or calibrate.

Conventional tensiometers exhibit significant diurnal measurement fluctuations from temperature changes in the transducer-tensiometer system (Watson and Jackson 1967) and the gases trapped in the tensiometer (Cassel and Klute 1986). As a result, the instruments have to be serviced regularly to remove air that can accumulate in the tensiometer and influence tensiometer measurements.

Tensiometers need to meet several requirements before they are used for monitoring landfills. They must: (a) operate from near land surface to depths exceeding 30 m, (b) be designed so that sensors can be checked for proper operation in the field, (c) allow calibration of the sensor, (d) permit replacement of the sensor if required, and (e) have reduced maintenance or servicing needs (monthly or preferably quarterly).

A new design for permanently installed tensiometers is presented. This design allows soil moisture potential measurements at any depth, reduces measurement errors from diurnal temperature effects, uses a replaceable transducer, allows in-place sensor calibration and verification, and reduces field maintenance requirements. This tensiometer has been named the advanced tensiometer. Advanced tensiometers were constructed and evaluated under field conditions. This paper presents construction details, installation procedures, and results of field trials.

MATERIALS AND METHODS

Figure 1 presents a cut-away of an advanced tensiometer. The pressure transducer assembly has a single hole rubber stopper or gasket on the bottom, a connector that attaches the stopper to the pressure transducer, and an inner guide pipe (1/2 in. schedule 40 PVC) that extends to land surface (Figure 1a). The connector allows pressure to be transmitted from the end of the stopper to the diaphragm of the transducer. The stopper size is chosen to firmly connect with the gasket throat of the adapter (Figure 1b). Electrical leads and an air line from the pressure transducer (gauge pressure) are contained within the inner guide and connect to a data logger (Figure 1c).

The permanently installed porous cup assembly consists of a porous cup bonded to a plastic adapter and PVC pipe that extends to land surface (Figure 1b). The adapter is machined to provide a seat to the pressure sensor (gasket throat), fitting between the porous ceramic on bottom and an outer guide pipe on top. The adapter is attached to commercially available tubing (outer guide pipe) which extends to land surface (1 in. class 200 PVC). A surface cap is placed on top of the outer guide pipe at land surface. The advanced tensiometer is formed by sliding the stopper, transducer, and inner tubing (Figure 1a) inside the outer guide tubing (Figure 1b) until the stopper/gasket seals to the adapter (Figure 1c).

Advanced tensiometers can be installed in any uncased borehole (>3.6 cm diameter). The porous cup, adapter and outer guide pipe are assembled at land surface and lowered to the specified monitoring depth. The outer guide pipe should be kept straight in the borehole so the stopper can make a good connection with the adapter. The borehole can be backfilled with a permeable material adjacent to the porous cup and with low permeability materials (bentonite or grout) between the monitored

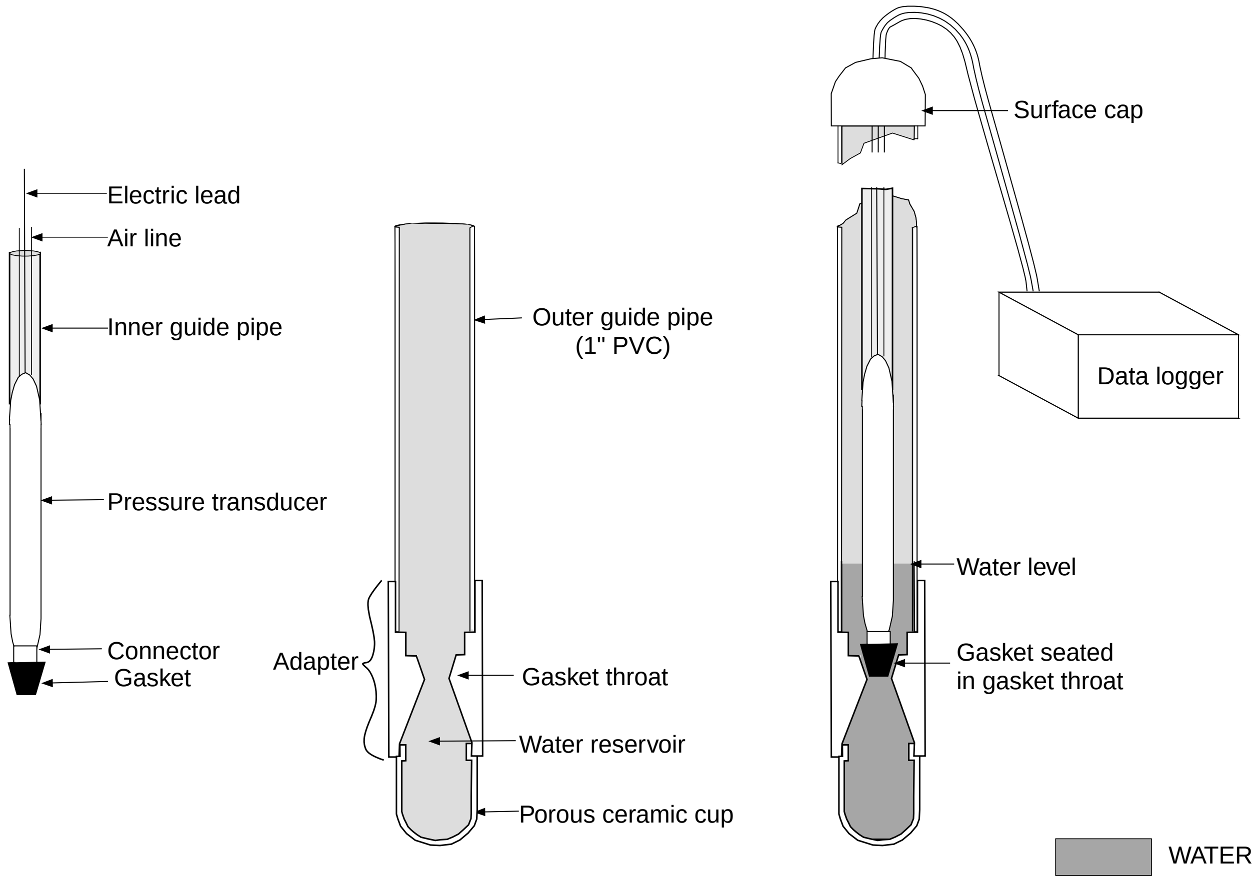


Fig. 1. Configuration of an advanced tensiometer.

intervals. Backfill techniques are presented by Morrison (1983) and Cassel and Klute (1986).

The advanced tensiometer is activated by filling the water reservoir with water and seating the stopper/transducer into the gasket throat. About 100 ml water is poured between the inner guide pipe and outer tensiometer assembly and the inner guide pipe assembly is raised a few cm to fill the cup and adapter (Figure 1c). The weight of the inner guide pipe and transducer presses the stopper into the adapter while the water moving from the reservoir into the surrounding unsaturated sediments applies a force that also holds the stopper in place.

The advanced tensiometer is serviced (deaired) by raising the inner guide pipe allowing the water reservoir to refill from water located above the stopper. Servicing should be performed before readings are affected by air entrapment in the water reservoir. The inner guide pipe and stopper only need to be pulled up a few cm. Water is added to the tensiometer periodically to maintain a small volume of water above the stopper. Excess water that is not required to fill the sealed bottom chamber adjacent to the porous cup is retained above the stopper and used to fill the chamber at a later time. The tensiometer readings equilibrate in a few hours following servicing.

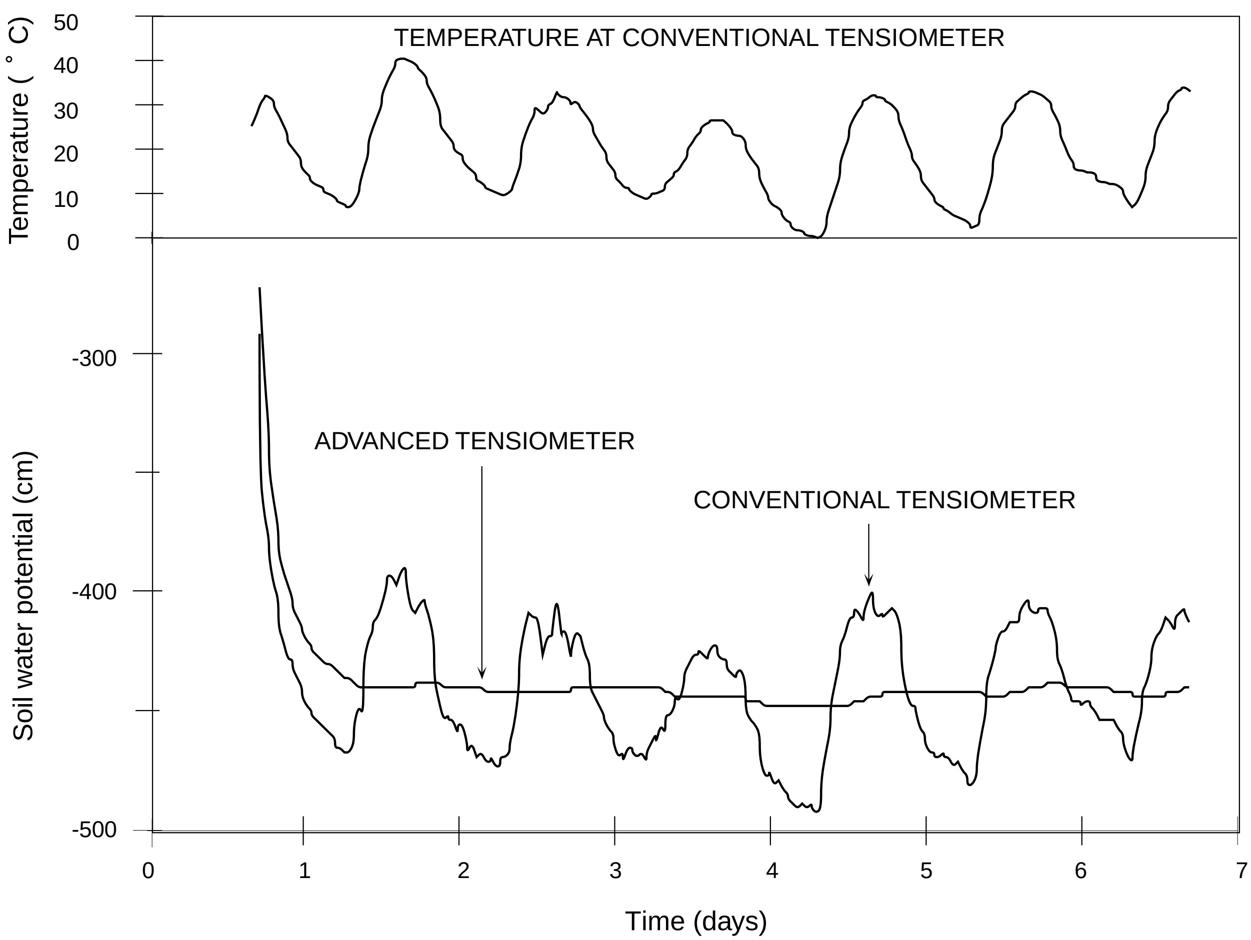
Calibration procedures were developed for pressure transducers used in the advanced tensiometer. The advanced tensiometers can be deaired or the transducers replaced in a few minutes from land surface. The transducer's calibration (y-intercept and slope) can be tested without having to remove it from the borehole. The y-intercept is determined by pulling the transducer upward out of the water, and then sensing the value with the data logger, while the air line is open to the atmosphere. The slope is determined following the y-intercept calculation by sealing the air line at the data logger, applying a known pressure on the air line and recording the pressure from the transducer. The pressure applied on the air line corresponds to the measurement recorded on the data logger.

Data from field tests comparing a conventional tensiometer (Soilmoisture Equipment Corp., Santa Barbara CA), and an advanced tensiometer are presented. A single 1.3 m deep by 10 cm diameter borehole was hand augered in Paul silty clay loam. The porous cups of the two instruments were set adjacent to each other and the borehole backfilled with native materials that was tamped into place. Pressure measurements were obtained on 30 min increments with temperature compensated +-15 psi transducers (Electronic Engineering Innovations, Las Cruces NM) using a data logger (Tumult Gadara, Brookline NH). The transducer on the conventional tensiometer was covered with a 1.2 cm thick plastic insulation and reflective foil. Temperature was recorded at the conventional tensiometer using a model 107b temperature probe and a 21X data logger (Campbell Scientific, Inc., Logan, UT).

Water usage with time was determined by placing a conventional and advanced tensiometer in a fallow field in Bannock loam at 6-inch depth with the porous cups a few cm apart. The instruments were filled with water and allowed to run for a week. The instruments were disassembled and the volume of water required to refill the tensiometers recorded.

Long term reliability of the advanced tensiometers is shown by operating four instruments at depths of 1.3 to 4 m in sediment for over 90 days without maintenance. A 15 cm borehole was augered in Pancheri loam and four

Fig. 2. Water potential from advanced and conventional tensiometers over a 6 day period.



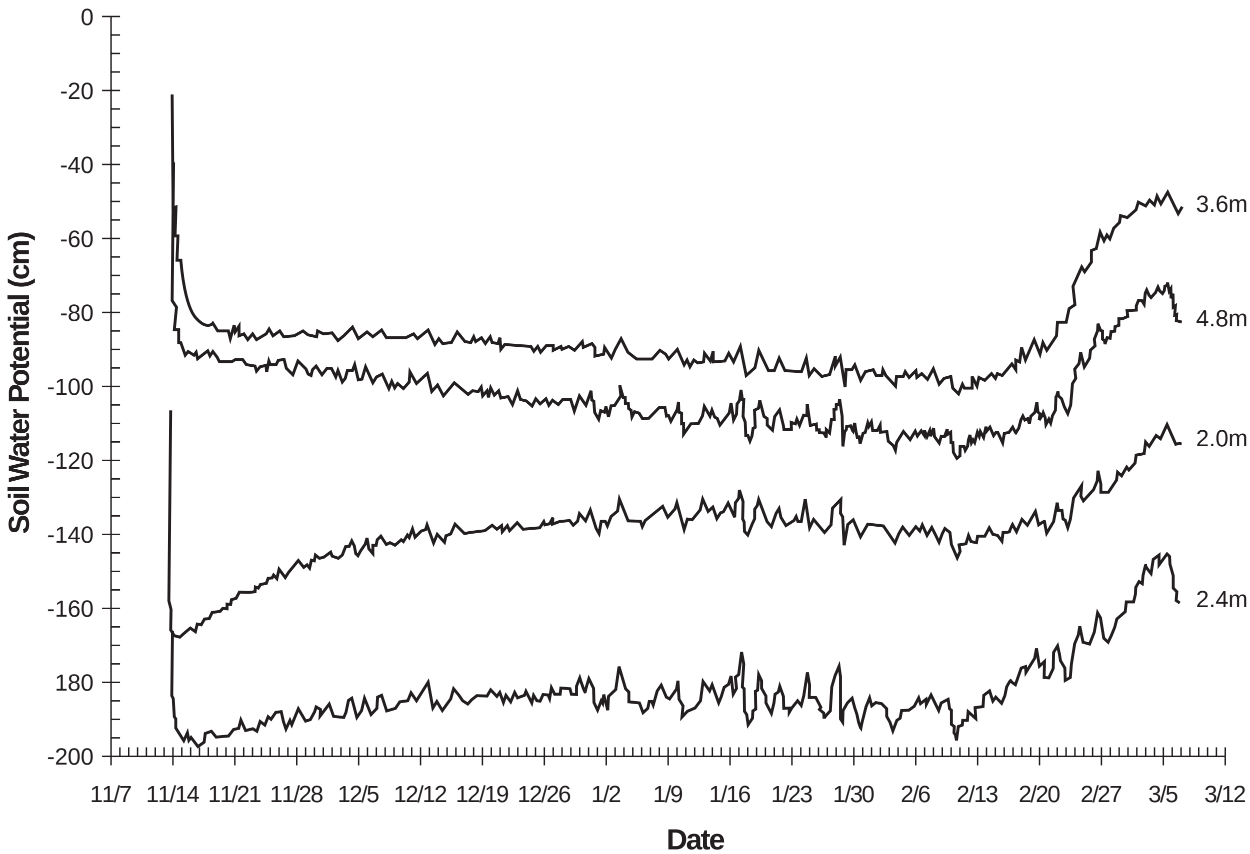


Fig. 3. Water potential measurements from advanced tensiometers over 90 days at 2, 2.4, 3.6 and 4.8 m depths.

advanced tensiometers installed using native backfill with 10 cm layers of bentonite separating the monitored intervals. Water potentials were obtained on 1 hour increments.

RESULTS AND DISCUSSION

Figure 2 presents six days of soil water potential data from a conventional and advanced tensiometer at 1.3 m depth along with temperature data at the conventional tensiometer. The advanced tensiometer readings stabilized to about -440 cm water potential in a day while the conventional tensiometer varied from -400 to -490 cm water potential. The large oscillations in readings of the conventional tensiometer are primarily due to temperature fluctuations from the transducer, expanding air in the headspace above the water column, and materials in the tensiometer. It is difficult to determine the actual soil water potential with the conventional tensiometer without averaging measurements. These diurnal fluctuations can also make it difficult to see subtle short term water potential changes. If manual measurements were obtained in the field at the same time each day using conventional tensiometers, trends in the data likely would be missed. Soil water potential data obtained from the advanced tensiometer on days 4-6 varied only 8 cm (439 to 447 cm) while the conventional tensiometer varied more than 90 cm. In this test, the diurnal fluctuations of soil water potential were reduced an order of magnitude by placing the water reservoir and pressure transducer below land surface. These data show that the advanced tensiometer has more stable measurements than the conventional tensiometer.

The advanced tensiometer can operate for extended time periods without servicing (deairing) compared to conventional tensiometers. Air in the tensiometer tends to degrade the readings, dampens the response to soil water potential changes, and may cause failure of the tensiometer if sufficient air enters. Conventional tensiometers accumulate air when water moves in and out by temperature induced pressure changes (Cassel and Klute 1986). Apparently not all of the water drawn out returns to the tensiometer. A test of water withdrawn from a conventional and advanced tensiometer indicated the conventional tensiometer filled with air at a rate four times that of the advanced tensiometer. The conventional tensiometer required 25 ml of water while the advanced tensiometer only required 6.5 ml to refill the tensiometers following the 7-day test. This suggests that the advanced tensiometer will operate without maintenance for longer periods of time than conventional tensiometers.

Lowering of the water level within the advanced and conventional tensiometers will affect the soil water potential measurements. The water reservoir on the conventional tensiometers is long and narrow (9 mm diameter) whereas the advanced tensiometer has a short large-diameter water reservoir. A loss of 50 ml in a conventional tensiometer lowers the measured head by 30 cm. The advanced tensiometer should only lose about 13 ml which corresponds to a water level change of 2-3 cm head.

A long term test was carried out using four advanced tensiometers placed at depths of 2, 2.4, 3.6, and 4.8 m. Tension values were recorded over a 90-day period (Figure 3). No water was added to these instruments during this test. In general, the soil water potential is relatively constant from November to February at all four depths. The instrument at 2 m shows an increase in soil water potential, with a period of stability, suggestive of wetting. The tensiometer at 2.4 m shows a similar but muted trend. Tensiometers at 3.6 and 4.8 m show an overall decrease in soil water potential of about 15 cm over the time period. These instruments operated over the entire winter without adding chemicals to prevent freezing. The instruments initially took 1 to several days to equilibrate with the surrounding sediments. The measurements show some variation over time that is related to changes in barometric pressure. The effects of barometric fluctuations on ground water are well-documented (Jacob 1940; Freeze and Cherry 1979; Rasmussen and Crawford 1997). In ground water, the barometric pressure changes are dependent upon the barometric efficiency of the well and can cause fluctuations in water level about 6 cm per day and up to 36 cm per year (Turk 1975; Hare and Morse 1997). Techniques to remove barometric effects by models and convolution algorithms are presented by Weeks 1979; Rojstaczer 1988a and b; and Rasmussen and Crawford 1997.

CONCLUSIONS

A permanently installed advanced tensiometer for measurement of soil water potential was presented and evaluated. The advanced tensiometer has a porous cup, water reservoir and outer guide tube that are permanently installed, with a pressure transducer and inner guide pipe that can be removed from the instrument. The instrument can be installed to nearly any depth from 0.15 m to greater than 30 m. The transducer can be calibrated in place without removing the transducer to land surface or it can be removed and replaced if it is inoperative. The tensiometer can be deaired and refilled with water from land surface in a few seconds. Placing the transducer at the bottom of the borehole increased the length of time between purging events to remove entrapped gases and reduced the diurnal measurement fluctuations seen in tensiometers with the pressure transducer at land surface. Continuous soil water potential measurements were obtained for a period of over 90 days without adding water to the tensiometer. The length of the hanging water column is nearly the same for all the advanced tensiometers allowing the data to be treated as matric potential by subtracting this length. This simplifies the analysis of the data since a file of these lengths does not have to be maintained. The advanced tensiometer can also operate during periods where the surface temperature is below 0ºC if the porous cup and transducer is below the frost depth. This reduces field maintenance on the tensiometers and permits monitoring throughout the year to capture episodic events such as snow melt. Thus, the advanced tensiometer can be used to measure soil water potential for long-term monitoring at shallow and deep depths with little instrument maintenance.

ACKNOWLEDGMENTS

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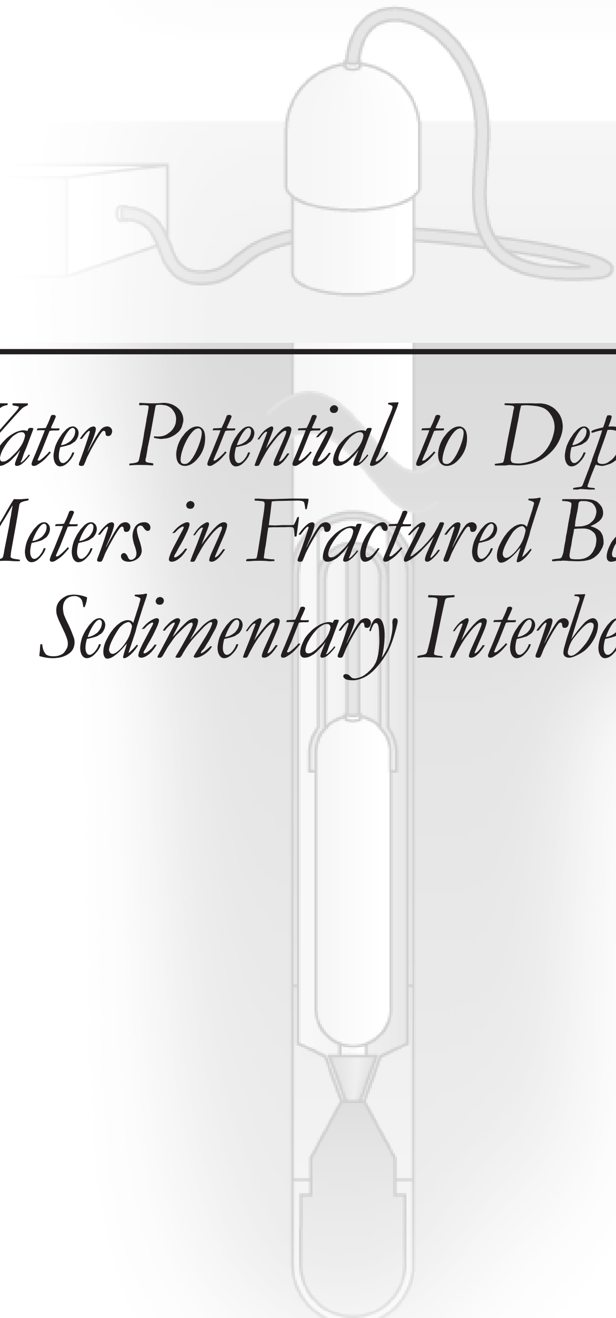

Water Potential to Depths of 30 Meters in Fractured Basalt and Sedimentary Interbeds

Part 2

Water Potential to Depths of 30 Meters in Fractured Basalt and Sedimentary Interbeds

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ABSTRACT

Water potential data are important for estimating moisture flow through the unsaturated zone at waste disposal sites. This paper discusses the results of a study conducted to determine whether tensiometers could be used to monitor moisture conditions at depths of concern at disposal sites. Tensiometers were installed at two sites at depths ranging from 3 to 30 m in porous rock and sedimentary interbeds. These measurements were made with tensiometers modified by placing the pressure sensor in close proximity to the porous ceramic cup. At one site the water potential ranged from -250 to -70 cm and appeared relatively constant over the 7-month monitoring period. At the second site the water potentials ranged from -250 to +100 cm, and data indicated two infiltration events occurred over the 16-month monitoring period. The results of the study indicate that water potential at depths of concern at waste disposal sites can be monitored by using the modified tensiometers.

INTRODUCTION

Infiltration and drainage at waste disposal sites control contaminant migration to underlying aquifers. Water potential measurements can be used to identify infiltration and drainage conditions below a waste site, and gradients in the total water potential indicate the direction of moisture movement. Changes over time in the water potential indicate seasonal infiltration and drainage. Because tensiometers directly measure the soil water potential, they provide soil water potential measurements that are more precise than other techniques [*Everett et al.,* 1984]. However, tensiometers must meet several criteria to be useful for monitoring at waste disposal sites: (1) the ability to operate at depths below the level of buried waste, (2) the capability of providing continuous, easily interpreted output that can be evaluated in real time, (3) the ability to operate for several months without maintenance, and (4) the capability to allow calibration in the field. A tensiometer that meets these criteria is the Advanced Tensiometer [*Hubbell and Sisson,* 1998]. An additional requirement for using tensiometers at the Idaho National Engineering and Environmental Laboratory (INEEL) is the ability to monitor water potential in porous rock.

PRELIMINARY ANALYSIS

At depths below a waste site, the water potentials will be similar to those found for a soil column that is undergoing gravity drainage. When profiles are undergoing gravity drainage (e.g., unit gradient), the flux is approximately equal to the hydraulic conductivity, K. A frequently used hydraulic conductivity water potential relationship K(h) is given by *van Genuchten* [1980]

$$K(h)=K_s \frac{\{1-(\alpha|h|)^{n-1}[1+(\alpha|h|)^n]^{-m}\}^2}{[1+(\alpha|h|)^n]^{-m/2}}$$

where h is the water potential, K_s is the saturated hydraulic conductivity, α and n are curve fitting parameters, and m=1-1/n. Parameters for selected soils and basalt are presented in Table 1.

TABLE 1. Properties of selected soils and materials.

Material	θ_s	θ_r	K_s	α	n
Hygiene sandstone	0.25	0.153	108	0.0079	10.4
Touchet silt loam G.E.3	0.469	0.19	303	0.005	7.09
Silt loam G.E.3 *	0.396	0.131	4.96	0.00423	2.06
Guelph loam drying*	0.52	0.218	31.6	0.0115	2.03
Beit Netofa clay	0.446	0	0.082	0.00152	1.17
W02 silt (Material 1)	0.5	0.06	21.6	0.01	1.6
W02 sand (Material 5)	0.44	0.038	578.4	0.04	2.55
W02 sandy silt (Material 8)	0.51	0.12	45.6	0.025	1.59
W02 silt (Material 12)	0.50	0.14	14.4	0.0036	1.58
W02 sandy silt (Material 15)	0.51	0.12	24	0.009	1.59
W02 basalt (Material 16)	0.23	0.015	24	0.0384	1.474

Sources: *van Genuchten* [1980]; *Martian and Magnuson* [1994].

Table 2 was constructed assuming a unit gradient and solving for the water potential at the assumed fluxes (i.e., hydraulic conductivities). The fluxes chosen were 11 cm/year (the currently accepted value for the annual infiltration rate below portions of a waste disposal site at the INEEL), 3.15 cm/year (i.e., 1.0E-7cm/second—a value commonly recommended for clay liner construction), and an arbitrary value of 1 cm/year. The water potentials given in Table 2 are in tensiometer range with the notable exception of W02 silt (Material 12). Thus, most soils should be in the tensiometric range at waste sites in which there is downward water movement.

TABLE 2. Water potentials (cm) at the given flux, assuming a unit gradient.

Material	Flux 11 cm/year	3.15 cm/year	1 cm/year
Hygiene sandstone[a]	172	181	190
Touchet silt loam G.E.3[a]	334	360	385
Silt loam G.E.3[a]	488	667	869
Guelph loam drying[a]	283	381	494
Beit Netofa Clay[a]	2	69	252
W02 silt (Material 1)[b]	349	517	728
W02 sand (Material 5)[b]	112	139	170
W02 sandy silt (Material 8)[b]	176	260	366
W02 silt (Material 12)[b]	856	1284	1820
W02 sandy silt (Material 15)[b]	402	597	841
W02 basalt (Material 16)[b]	96	149	216

a. *van Genuchten* [1980]
b. *Martian and Magnuson* [1994]

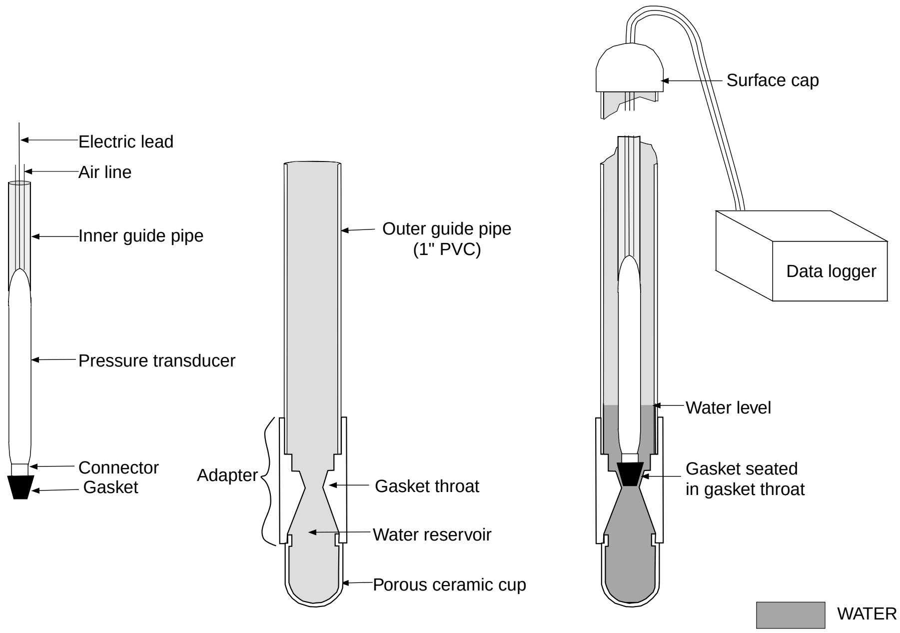

Fig. 1. Internal design of the Advanced Tensiometer (Hubbell and Sisson, 1998).

METHODS AND MATERIALS

Figure 1 presents the modified tensiometer (i.e., Advanced Tensiometer) showing its component parts: a permanently installed casing (1b) and a removable transducer assembly (1a). The permanently installed casing is equipped with a porous ceramic cup on the bottom, an adapter containing a reservoir of water, and casing that extends to land surface. The removable electronic pressure transducer assembly consists of a rubber gasket and pressure transducer attached to an inner guide tube for installing the transducer assembly from land surface. The transducer assembly is lowered into the casing until the gasket seats into the permanently installed adapter. The Advanced Tensiometer is activated by filling the porous cup/adapter with water, sliding the pressure transducer assembly (1a) inside the casing (1b) until the stopper/gasket seats in the adapter (1c). Additional details on construction and installation of Advanced Tensiometers are presented by *Hubbell and Sisson* [1998].

Two wells were instrumented with Advanced Tensiometers at depths of 3 to 30 m, and data were collected for 7 and 16 months in southeastern Idaho (Figure 2). Well 76-5 is located in the southern portion of the INEEL. Well IRC-3 is located in Idaho Falls, about 70 km east of Well 76-5. Both sites are located on the Snake River Plain, which is composed of Quaternary volcanics (olivine basalt) overlain by loess and stream channel deposits [*Hackett and Smith,* 1992[. The INEEL and Idaho Falls are located on the Eastern Snake River Plain (ESRP), which is a large flat valley surrounded by mountains that rise to about 3,300 m. The ESRP is generally classified as arid to semiarid with an annual precipitation of 200 to 300 mm. The 76-5 site receives about 250 mm of precipitation annually, and the IRC-3 site receives 300 mm annually [*Clawson et al.*, 1989]. The average snowfall is about 700 mm with maximum average accumulations of about 100 mm in January and February. The average summer temperature is 28°C and the average winter temperature is -0.6°C.

Well 76-5 was air rotary (core) drilled and sampled with a 14.9-cm-diameter bit to a depth of 73 m. The bottom of the well was sealed to a depth of 32 m. Figure 3 presents the stratigraphy of Well 76-5. The well has loam

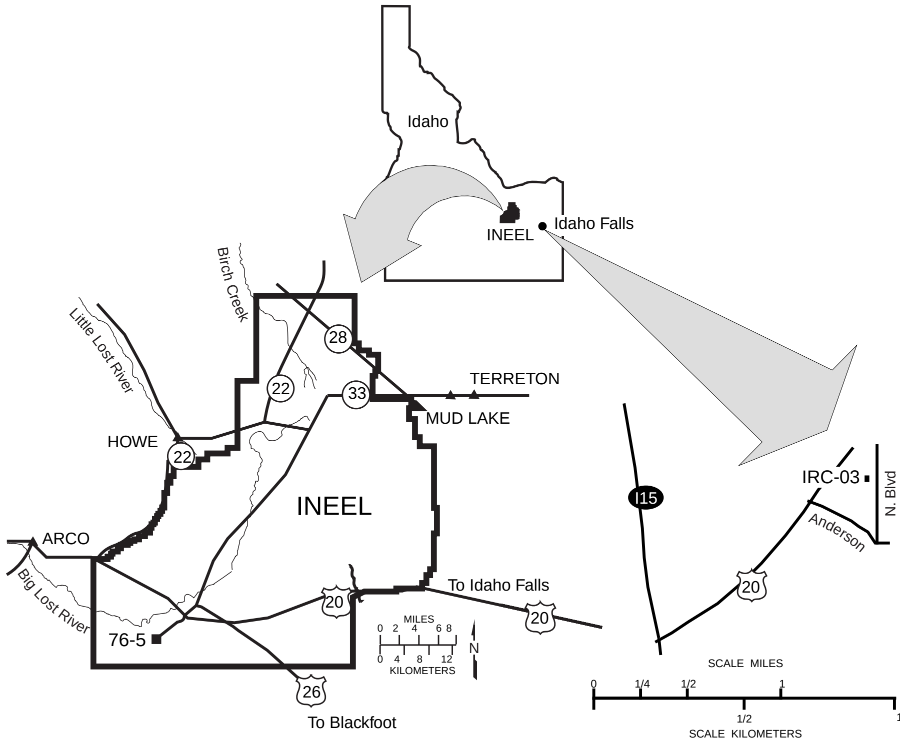

Fig. 2. Location of wells 76-5 ad IRC-03

backfill and undisturbed loam from land surface to basalt at about 4 m. Basalt is located from about 4 to 9.4 m and from about 10.4 to about 31 m. Sedimentary interbeds composed of loam materials are located between the basalts. The basalt has a relatively high porosity of about 0.22 m^3 m^{-3}, a permeability of about 1E-6 cm/second, and a low water retention capacity of about 1 to 5 m^3 m^{-3} at 100 cm of tension [*Bishop*, 1991]. The loam has a porosity of about 0.45 m^3 m^{-3}, a saturated hydraulic conductivity of about 1E-5 cm/second, and a water retention capacity of about 0.40 m^3 m^{-3} at 100 cm [*McElroy and Hubbell,* 1990].

Drillers, video, geologic, and geophysical logs were examined and evaluated to determine the optimum depths for locating tensiometers adjacent to the rubble zones, sedimentary interbeds, sediment infilled fractures, and basalt that appeared moist. Well 76-5 was backfilled and instrumented with Advanced Tensiometers in June 1996. The well was backfilled with a layer of silt loam 0.3 to 1 m thick placed adjacent to the porous cups on the tensiometers and granular bentonite layers (about 0.3 m) placed between the monitoring depths. Course sand Number 6-8) was used to fill the remaining portions of the well between the tensiometer monitoring depths [*Cassel and Klute*, 1986].

The lithology of the instrumented depths is presented in Figure 3. The uppermost tensiometer was placed adjacent to the first sediment-filled fracture in basalt below the surficial sediment. The second tensiometer was placed adjacent to a sedimentary interbed at about the 9-m depth. The next three tensiometers were installed adjacent to sediment infilled fractures within basalt. A tensiometer was located adjacent to moist unfractured basalt a few meters above a sedimentary interbed and the lowermost tensiometer was placed adjacent to a sedimentary interbed comprised of clayey silt at about the 31-m depth. Several pressure transducers in the tensiometers failed over the test period, and the data from those tensiometers were omitted.

Well IRC 3 was drilled to a depth of 15.2 m in September 1995 using the air rotary drilling technique with a 14.9-cm-diameter bit. The well is located in the same general geologic formation as Well 76-5 (in Snake River Plain basalt). The site is characterized by loam and

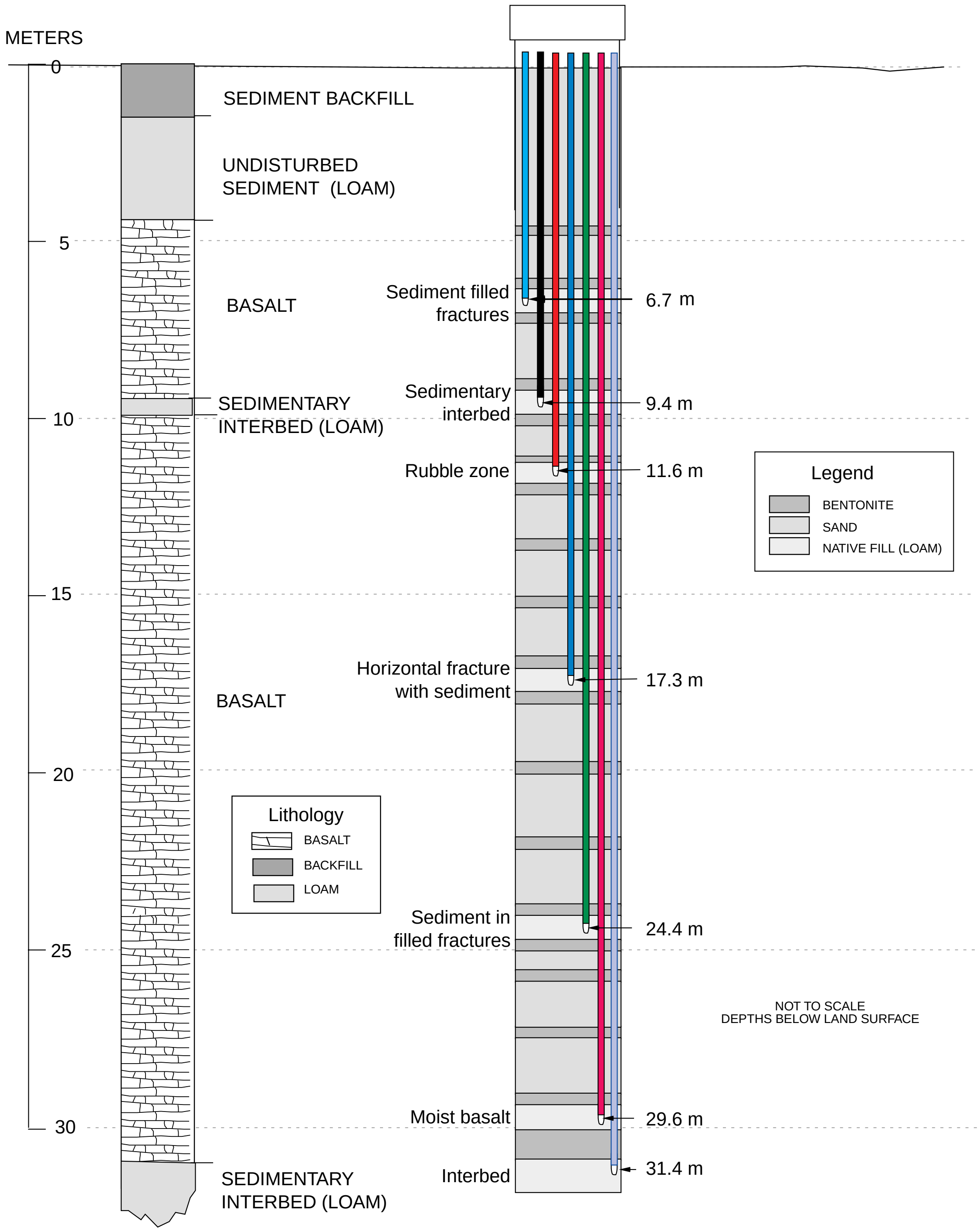

Fig. 3. Geologic log and completion diagram for 76-5.

alluvial sediment extending from land surface to a depth of 2.7 m and basalt from 2.7 to 15.5 m (Figure 4). Sedimentary interbeds were not present at this site.

Tensiometers were located at the sediment-basalt contact, adjacent to nonfractured basalt, fractured basalt, and “moist” or “wet” nonfractured basalt based on examination of

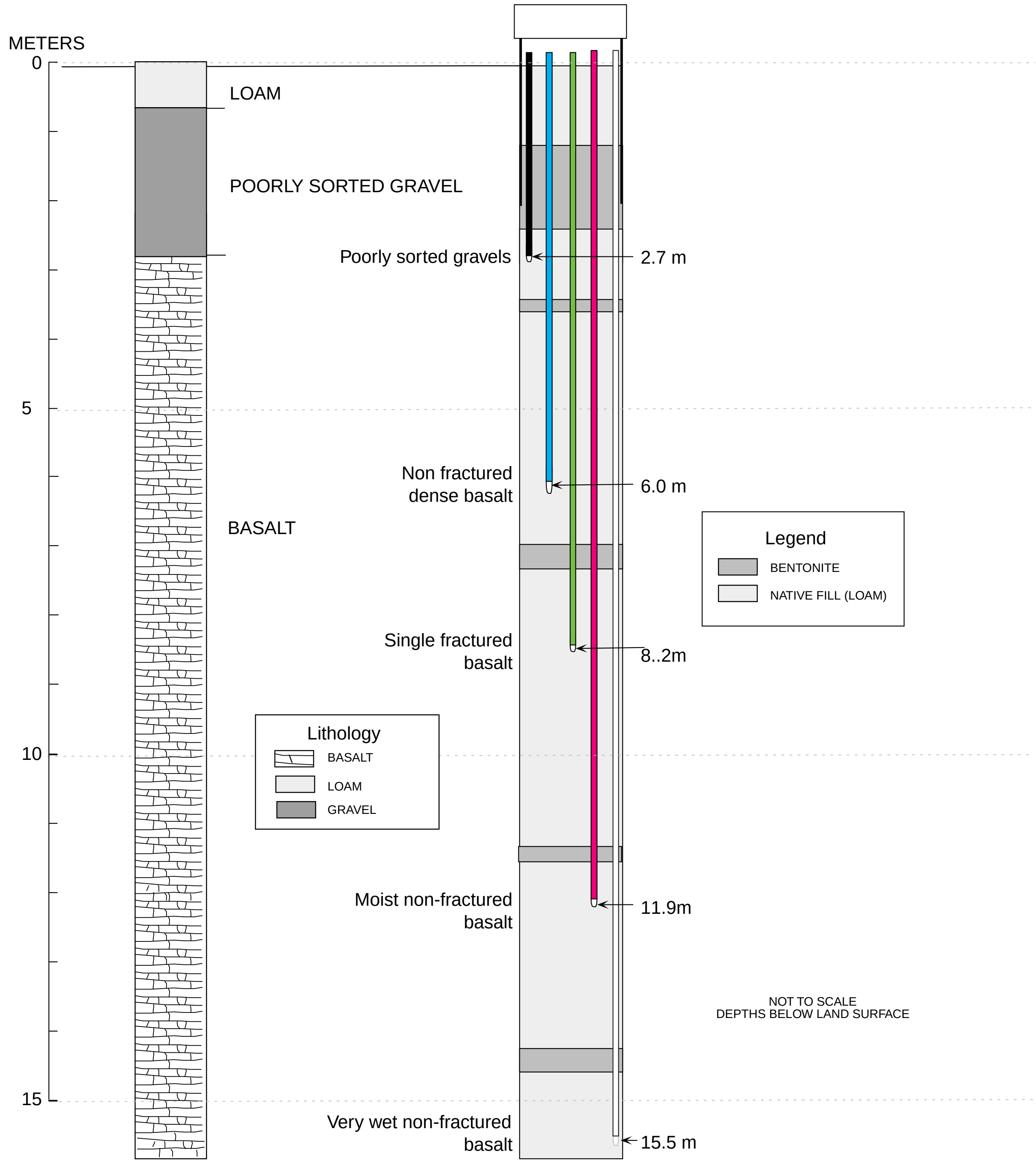

Fig. 4. Geologic log and completion diagram for Well IRC-03

drillers, video, caliper, gamma, and neutron logs. During the installation of the tensiometers, the well was backfilled using the technique outlined in *Cassel and Klute* [1986]. The construction of the well varied from Well 76-5 in that loam was used to backfill most of the borehole with a single layer of bentonite 0.3 to 0.6 m thick placed between the monitored intervals

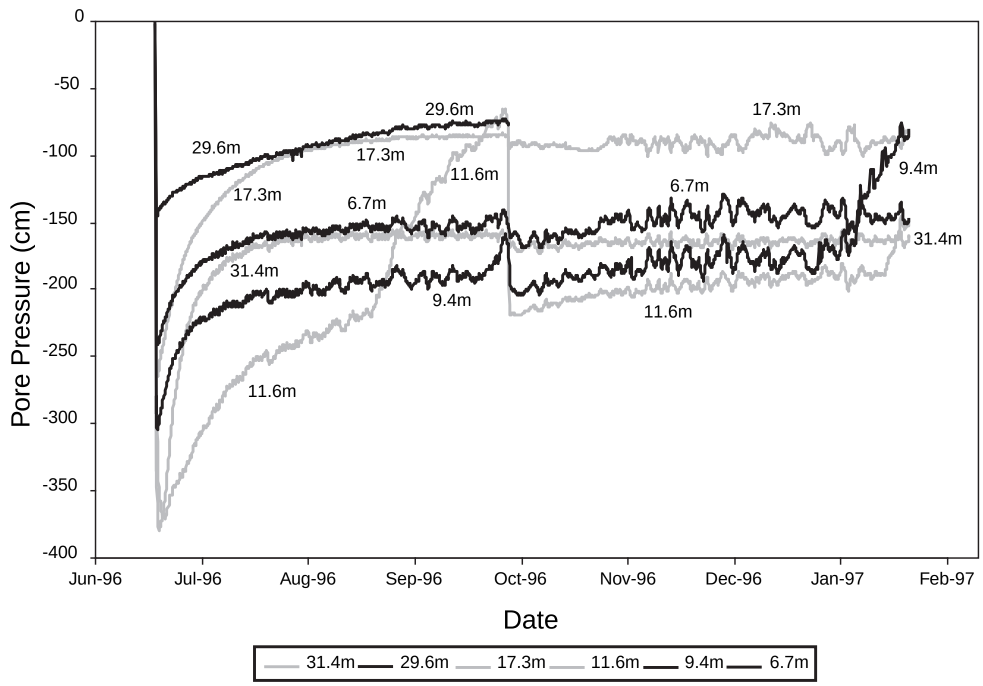

Fig. 5. Soil water potential data from Well 76-5.

(Figure 4). The shallowest tensiometer is placed adjacent to a sandy gravel at the sediment-basalt interface, and the other four tensiometers are located adjacent to dense or fractured basalt.

RESULTS AND DISCUSSION

Figure 5 presents water potential data from Well 76-5 for the period from July 1996 through February 1997. Water potentials initially were in the range of -375 to -150 cm and increased over several months to a range of -220 to -70 cm. Low initial water potential measurements in July and August 1996 are representative of the sediment (loam) used to backfill around the tensiometers. Sediment used for backfill had water potentials at about -300 to -400 cm of pressure before placement in the boreholes. The tensiometers equilibrated with the backfill in a few hours to days while the backfill took several weeks at the 17.3-m depth and more than 2 months at the 9.4-m depth to equilibrate with the water potential in the surrounding basalt. This equilibration time is related to the time for moisture to move from the basalt into the drier sediment backfill. The tensiometer measurements show a rapid increase in pressure that levels off as the pressure approaches an equilibrium range. The tensiometer measurements do not approach a single value but vary over a range of about ± 20 cm. These fluctuations were found to be correlated to changes in barometric pressure.

Water potential appeared to be unaffected by daily or yearly infiltration events at these depths. The total variation in water potential was less than 50 cm in all the tensiometers over the 7-month period. The gradients in total water potential were found to be near unity, which indicates that water was moving downward. The highest water potentials were located in the basalt while the sedimentary interbeds generally had lower potentials. The trend of higher water potential in basalt was assumed to be related to the basalt having a lower unsaturated hydraulic conductivity than the interbeds, and thereby retained more water. The trend corresponds with modeling results obtained by *Martian and Magnuson* [1994] using the UNSAT-H code [*Fayer and Jones*, 1990].

The apparent increase in the water potential in the 11.6-m tensiometer from September to

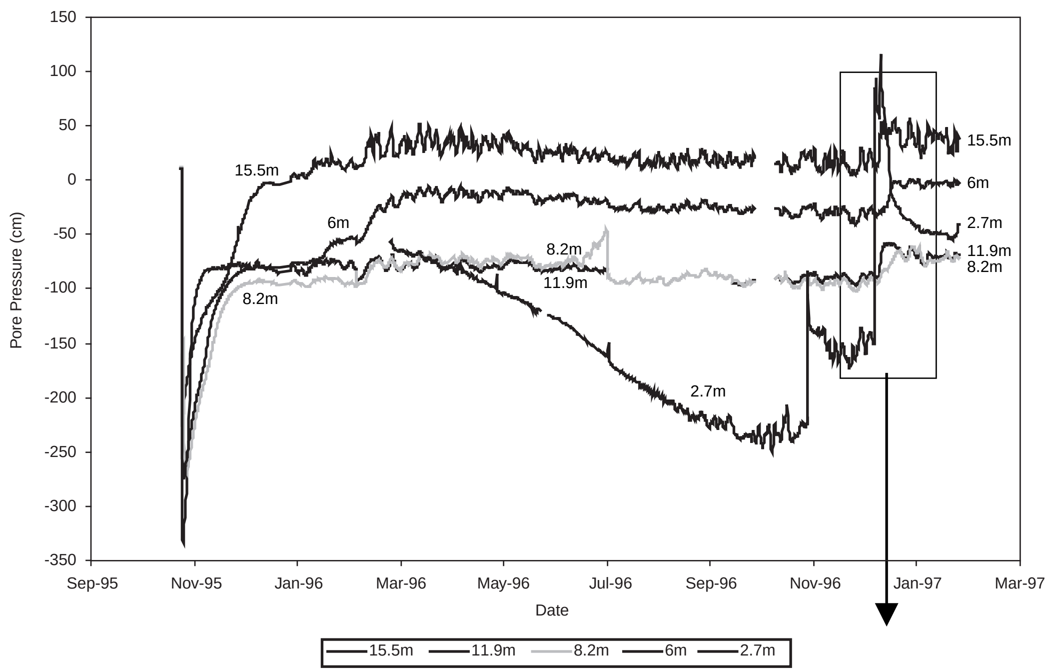

Fig. 6. Soil water potential from Well IRC-03.

mid-October reflects air entering the tensiometer and lowering of water in the instrument and is not an increase in the actual water potential. Similar trends were recorded at the 9.4- and 11.6-m depths in January 1997. The tensiometers were filled with water at the beginning of the test in June 1996, in mid-October, and at the end of the test in February 1997. This data indicated that the tensiometers operated for more than 3 months without filling with water, following initial equilibration.

Several pressure transducer measurements shifted slightly toward lower water potential (about 10 cm) after being refilled with water in October. The decrease in the water potential is assumed to be caused by changes in the hanging water column in the tensiometer. Filling the tensiometer with water maximizes the hanging water column, which decreases the apparent water potential.

In Figure 6, data from Well IRC-3 are presented for 16 months, from November 1995 to March 1997. Tensiometer measurements within basalt showed an initial period when the sediment used for backfill came into equilibrium with the surrounding basalt similar to the measurements for Well 76-5. Water potentials equilibrated to the range of +120 to -220 cm in all of the tensiometers. The tensiometers at 6- to 15-m depths indicated nearly constant values over the period of measurement. The 2.7-m tensiometer indicated a drying trend of -50 to – 220 cm from March to December 1996 then several wetting events from late December 1996 to March 1997.

Water potential data indicated several wetting events over the 16 months of measurements. The most pronounced occurred from a snow melt event in late December 1996 (Figure 7). The wetting front passed from the depth of 2.7 m to 15.5 m in a few days. All of the tensiometers responded to this infiltration event; however, the sequence of first arrival indicated preferential flow paths within the basalt. Following the formation of perched water at 2.7 m at the basalt-sediment interface, the water potential responded first at the 11.9- and 15.5-m depths and then a few days later at the 6-m and finally the 8.2-m depth. The greatest change in water potential caused by infiltration was observed at 15.5 and 11.9 m, adjacent to moist to wet nonfractured basalt and in dense nonfractured basalt at 6 m. The least

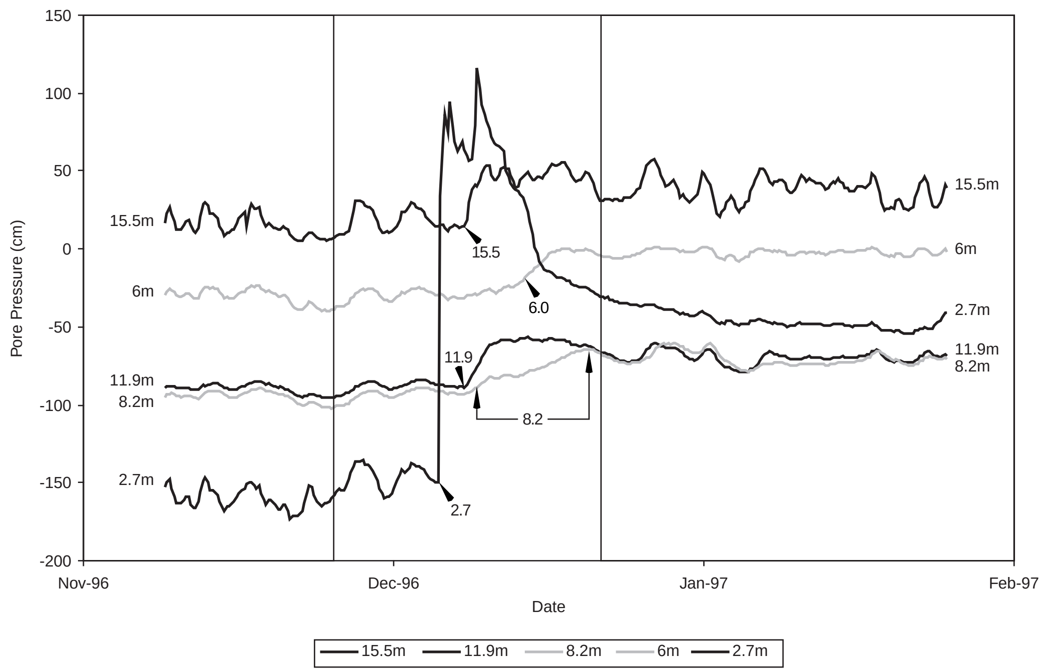

Fig. 7. Detail of infltration event in Well IRC-03

distinct response was recorded from the tensiometer adjacent to a single fracture at 8.2 m. These data show infiltration occurring rapidly through the basalt. The velocity of the water pressure pulse ranged from 1 m/day to 3 m/day through the basalt.

Several wetting episodes occurred during January and March 1996 after snow-melt and precipitation events. The January event indicated an increase in water potential of about 15 cm at the 6- and 15.5-m depths that was followed by a 20-cm increase in March 1996. Following the wetting episodes, the tensiometer measurements showed decreases in water potential until the wetting event in December 1996. These data indicated the water potentials changed quickly to infiltration events and more slowly to drainage. This would happen when wetting resulted from infiltration through preferential flow paths followed by drainage through the basalt matrix.

CONCLUSIONS

A comparison of water potential data from Wells 76-5 and IRC-3 indicated that all measurements are within the tensiometric range of +120 to -220 cm. Within basalt, Well 76-5 has lower water potentials from -70 to -220 cm while Well IRC-3 is in the range of +120 to -80 cm. Comparing similar depths, Well IRC-3 had water potentials of about 100 cm higher than Well 76-5. The higher water potentials may be caused by more infiltration having taken place at Well IRC-3 or by differences in hydraulic properties at the two sites.

Water potential trends over time varied between these wells. Tensiometers in Well 76-5 indicated nearly constant water potentials over the 7-month monitoring period, while Well IRC-3 had several increases in water potential over the 16-month monitoring period. Well IRC-3 showed a wetting front that moved to 15 m in a few days while Well 76-5 showed no evidence of formation of a wetting front during the same time period. The time for the water potentials within the loam backfill to equilibrate with the surrounding basalt was from several weeks to more than 2 months at both wells.

The relatively uniform water potentials obtained with depth indicated the hydraulic gradient to be downward and near unity at both wells. Thus water movement was downward at a rate near the hydraulic conductivity. Tensiometers in one well showed episodic moisture movement to depths of 15.5 m in a few days after snow melt events. Water potential measurements were affected by barometric pressure fluctuations, and equilibration time was found to depend on the backfill material used in installation and hydraulic conductivity of the porous material being monitored. Results indicated the Advanced Tensiometers can be used successfully to monitor moisture conditions in porous rock and sediments at waste disposal sites.

ACKNOWLEDGMENTS.

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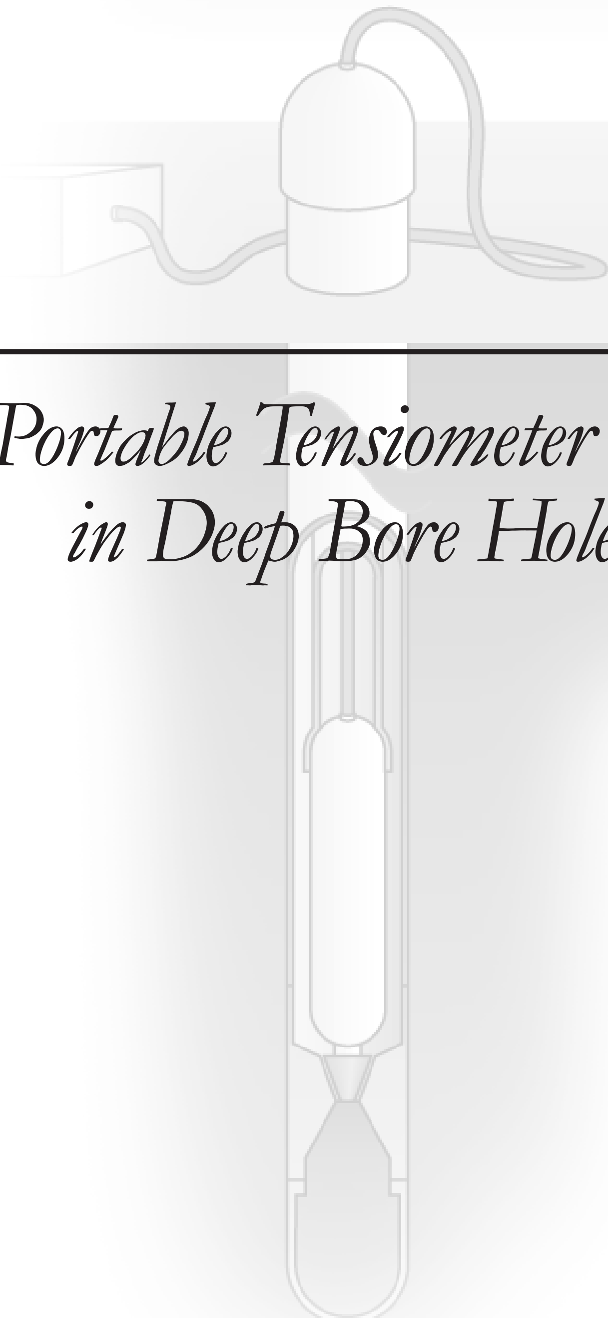

Portable Tensiometer Use in Deep Bore Holes

Portable Tensiometer Use in Deep Boreholes

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ABSTRACT

Quantifying the direction and rate of soil water movement beneath landfill disposal areas requires tensiometers capable of monitoring soil water potentials from one to several hundred meters below land surface. This paper describes a new way to use tensiometers to measure soil water potentials at nearly any depth. Two portable tensiometers were constructed and tested in the field. One portable tensiometer was sealed with a septum stopper, lowered to the bottom of a borehole, allowed to equilibrate, and retrieved to land surface. The soil water potentials were then determined through the septum stopper using a pressure transducer equipped with a hypodermic needle. A second portable tensiometer was constructed with an electronic pressure transducer with leads brought to land surface to allow continuous monitoring of soil water potentials without removing the tensiometer from the borehole for extended time periods. The portable tensiometers are retrieved to land surface periodically to refill with deaired water. Both portable tensiometers were operated in the field for periods exceeding 2 months with little maintenance at depths of 4-6 meters. The response time of the portable tensiometers ranged from a few hours to several days and was limited by the contact between the porous cup and the soil. The slow response time was not found to be a serious problem in deep boreholes. The nearly constant temperature conditions found in deep boreholes were found to contribute to stable, long-term tension values and to reducing maintenance normally required by standard tensiometers.

INTRODUCTION

Tensiometery is an established technique for obtaining accurate measurements of soil water potential between 0 and -1000 cm (Richards, 1928, Cassel and Klute, 1986). Multiple tensiometers in a profile can be used to determine hydraulic gradients to estimate the direction of water movement. The hydraulic gradients are used with the unsaturated hydraulic conductivity to estimate water flux. Tensiometers work in the water potential range associated with the highest unsaturated hydraulic conductivities and thus the greatest potential for water movement. The movement of water in the unsaturated zone is important for irrigation management practices (Cassel and Bauer 1976; Hagan et al. 1967), recharge studies (Sophocleous and Perry 1985), hazardous-waste site monitoring (Healy et al. 1984; Everett et al. 1984), and engineering studies (Wilson et al. 1995).

Standard tensiometers are generally installed within a few meters of land surface because the length of the water column connecting the porous cup to the pressure transducer adds to the vacuum in the tensiometer. Tensiometers may be constructed with the pressure transducer buried at or near the sensing tip to circumvent this depth limitation and allow automated data collection (Klute and Peters 1962; Williams 1978; Trotter 1984; Nyhan and Drennon 1990). However, this technique does not allow periodic calibration of the transducer or refilling of the instrument unless there is physical access to the pressure sensor (i.e. caisson). An air filled

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tensiometer was proposed to eliminate the depth limitations by Fabishenko (1986) by partially filling a lysimeter (tensiometer) with fluid and recording soil water potential using the fill tubes at land surface. Tokunaga (1992) and Tokunaga and Salve (1994) present results from tests of the air filled tensiometer, to optimize the fractional air filled length, absolute matric head, vapor pressure and the depth of the tensiometer porous cup in deep vadose zones. This technique works for permanently installed tensiometers (lysimeters) but is not installed on a temporary basis.

Another problem with standard tensiometers is that they frequently exhibit significant diurnal fluctuations in measurements primarily due to temperature changes of the material in the tensiometer (Cassel and Klute 1986) or the transducer-tensiometer system (Watson and Jackson 1967). These diurnal fluctuations are in part related to the limitation of shallow installation depth.

A new technique has been employed for tensiometers to obtain soil moisture potential measurements at nearly any depth. We call the tensiometer used with this technique a portable tensiometer. The portable tensiometer is lowered to the bottom of a borehole so the porous cup is in contact with sediment. Following a suitable equilibration time, the tensiometer is withdrawn to land surface to read the sensor or data is relayed to land surface by way of a pressure transducer/data logger.

Two portable tensiometers were constructed and evaluated in the laboratory and under field conditions. This paper presents construction details and installation procedures for the portable tensiometers and results of laboratory and field tests.

TENSIOMETER CONSTRUCTION AND INSTALLATION

Numerous configurations of tensiometers have been built since their conception (Gardner et al. 1922; Richards 1931; Morrison 1983; Cassel and Klute 1986; EPA 1993). While the construction of tensiometers can vary, all tensiometers consist of three basic components: a porous cup or plate, a pressure sensor, and a chamber filled with water that connects the porous cup to the pressure sensor.

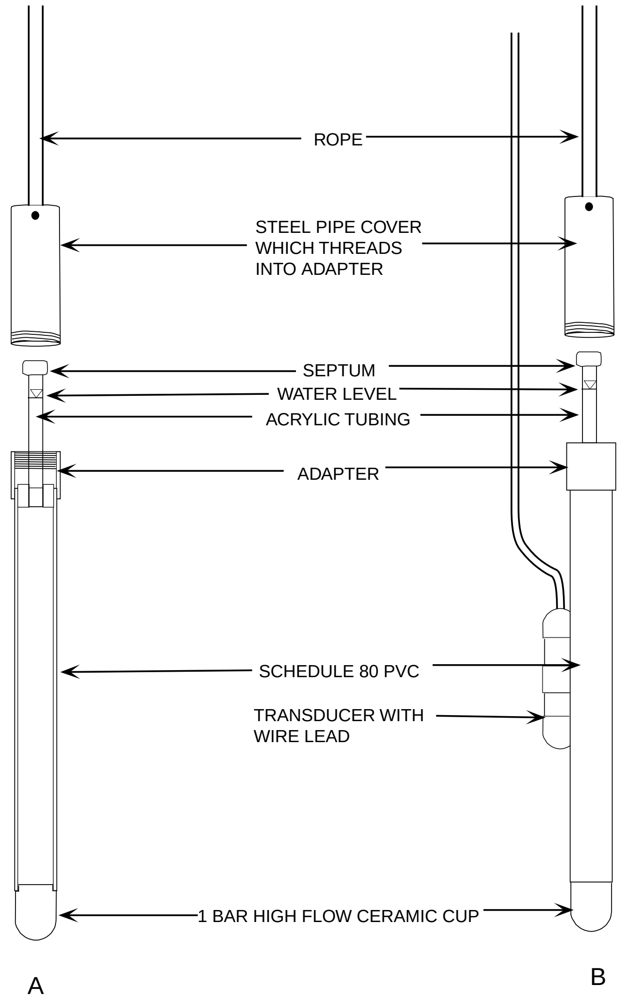

Fig. 1. Configuration of the portable tensiometers.

Figure 1a shows a cut-away of a portable tensiometer designed to obtain single measurements from the bottom of a borehole. The tensiometer is approximately 30 cm long. The portable tensiometer was sealed with a septum to reduce costs and the complexity of the instrument. Costs were considered important since operating the instruments at drill sites was found to increase the chance of breakage from rough handling. The tensiometer has a one-bar high- flow porous cup on the bottom, a chamber that contains water and a septum that seals the instrument. Acrylic tubing (3/8 inch) is used to visually determine the water level in the instrument. A length of steel

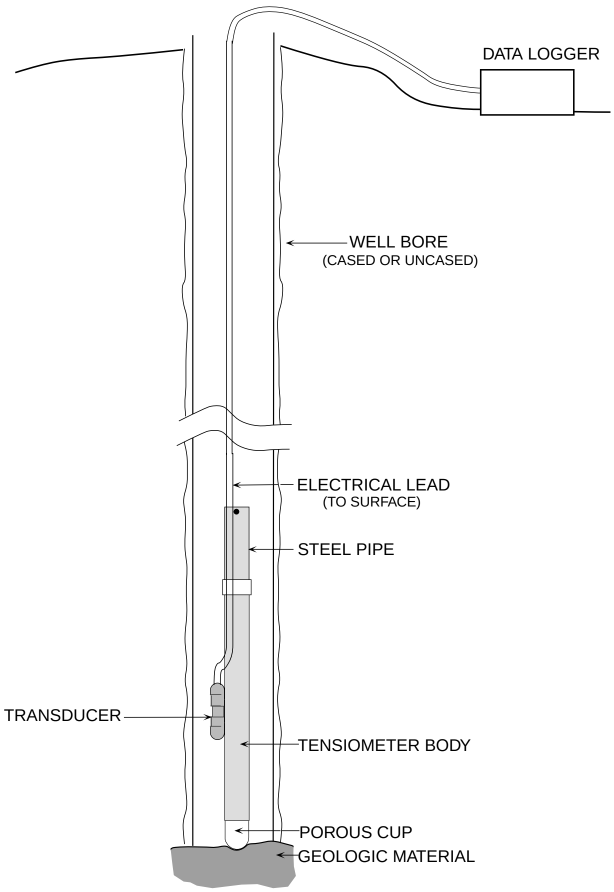

Fig. 2. Schematic showing field use of a portable tensiometer.

pipe (0.5 to 1.5 kg) threads into the top of the tensiometer to provide additional weight. Rope is connected to the steel pipe to install and retrieve the tensiometer. The portable tensiometer is retrieved to land surface and the septum penetrated with a hypodermic needle with a transducer attached to obtain a single measurement of the soil moisture tension in the sediment at the bottom of the borehole. The tensiometer in Figure 1b is equipped with a pressure transducer to obtain continuous soil water potential measurements over time.

A tensiometer was sealed with a septum and read using a syringe needle connected to a direct reading pressure transducer (Tensimeter™, Soil Measurement Systems, Tuscon, AZ). A Bourdon gauge was also used in place of the septum to obtain direct measurements. This instrument allowed single measurements to be collected following retrieval of the instrument to land surface. A second tensiometer was equipped with a pressure transducer, connected to a data logger at land surface, used to obtain soil water potential data for the 233-day test period and to obtain tensiometer response time data following installation.

The portable tensiometers were transported to the field in a short piece of PVC tubing with a cap holding a sponge against the ceramic cup. The porous cup was protected against breakage by the PVC tubing and kept moist by the wet sponge.

Once at the field site, the steel pipe was attached to the tensiometer and the entire assembly was lowered to the bottom of the borehole and allowed to equilibrate with the soil surface (Figure 2).

Conventional wisdom regarding tensiometer operation requires a through hydraulic contact with the soil in which it is emplaced. Standing a tensiometer on a soil surface limits the contact area between the porous cup and soils and could significantly impact the response time of the tensiometer. The response time provided by standing a tensiometer on a soil surface was evaluated in a laboratory study using a short soil column filled with Pancheri loam, fitted with a hanging water column, and instrumented with a conventionally installed tensiometer. After the hanging water column was set to a given tension, the portable tensiometer was placed on the soil surface and the water potential was monitored with an electronic transducer (Electronic Engineering Innovations, Las Cruces, NM) and data logger (Tumut Gadara, Columbus, OH). Moisture proof plastic film was placed over the hanging water column and portable tensiometer to reduce evaporation. Water potentials were obtained in 10-minute time increments from the portable tensiometer at the soil water potentials of 10, 55, 180, and 240 cm of water.

RESULTS AND DISCUSSION

The results of the laboratory response time test are shown in Figure 3. These results show that the limited contact provided by simply

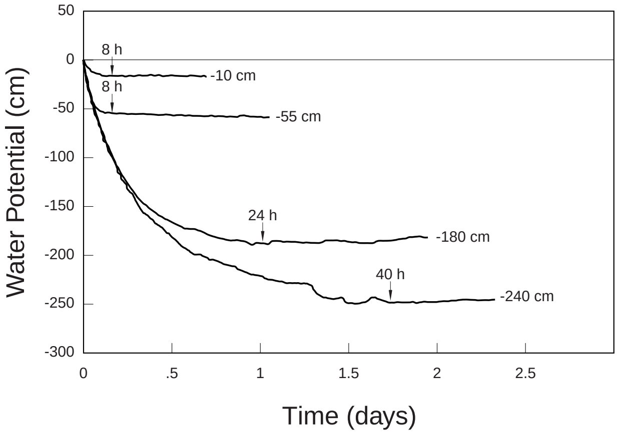

Fig. 3. Measurements from a portable tensiometer at water potentials of 10, 55, 180, and 240 cm versus time.

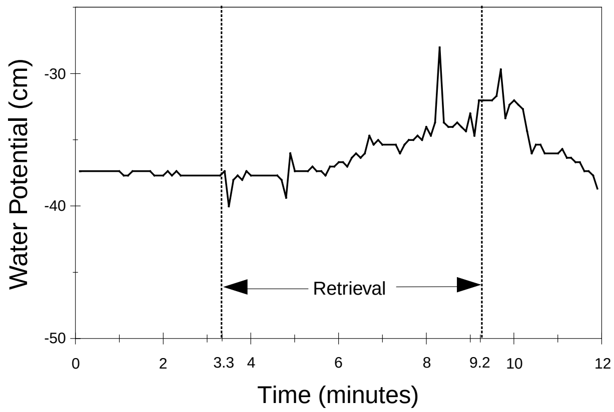

Fig. 4. Water potential measurements while retrieving the portable tensiometer to land surface.

placing the tip of a tensiometer on the soil surface can require 36 to 48 hours for the water potential to reach the final value of 240 cm. At higher water potentials, the response time is less than 24 hours. While a more than 24-hour response time could be critical under conditions of rapidly changing water potentials it was considered acceptable for installations several meters below land surface where water potentials are believed to change slowly.

The response time of the portable tensiometer is a function of the texture of the sediment, in situ water potential, hydraulic properties of the sediment, hydraulic properties of the porous cup, the area of contact, volume of air in the tensiometer, and the hydraulic connection to the sediment. The first three factors cannot be modified but the latter four can controlled within limits to decrease the time for equilibrated measurements. A larger cup size with a high conductivity will facilitate readings and increasing the weight of the tensiometer will press the porous cup with greater force to the sediment, increasing the hydraulic connection and decreasing the response time. Decreasing the volume of air in the portable tensiometer will reduce the volume of water required to move between the tensiometer and the sediment. If measurements are required over a limited time period a pressure transducer and recorder should be used to insure the pressure in the tensiometer have equilibrated with the in situ water potential.

The portable tensiometer designed to obtain single measurements during drilling operations requires retrieval to land surface, where the water potential is determined. The water potential indicated by a tensiometer was expected to change as the instrument was retrieved to land surface. The change in water potential during retrieval was evaluated using a tensiometer equipped with an electronic pressure transducer. The tensiometer was placed in a borehole, allowed to come into equilibration with the soil water for several days, and retrieved slowly to land surface while recording tension values (Figure 4). These data show that pulling the tensiometer away from the soil surface and retrieving to near land surface did not significantly change the water potential during retrieval (± 5 cm), provided the porous cup was not exposed to strong evaporative conditions such as direct sunlight or wind. The sharp transient spikes in the data are caused by acceleration effects from moving the transducer while recording a measurement. Tests at water potentials of -300 and -600 cm produced variations of 1-3 cm during tensiometer retrieval to land surface. Thus, a low-cost tensiometer can be used during lulls in drilling activities to obtain reconnaissance type data and aid in designing final well completion.

The portable tensiometer needs to have long term stability to identify trends in water movement patterns in addition to a quick response time and reproducible results. A long

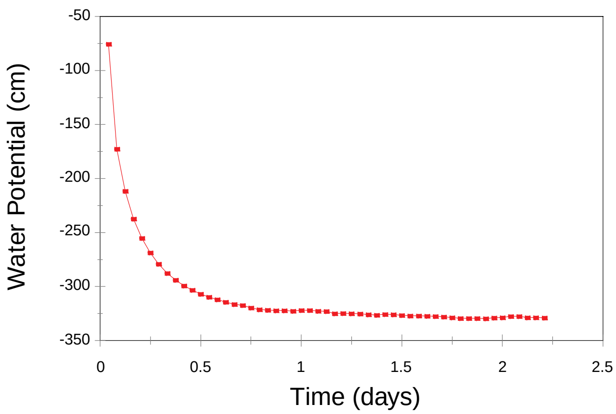

Fig. 5. Borehole tensiometer response time results.

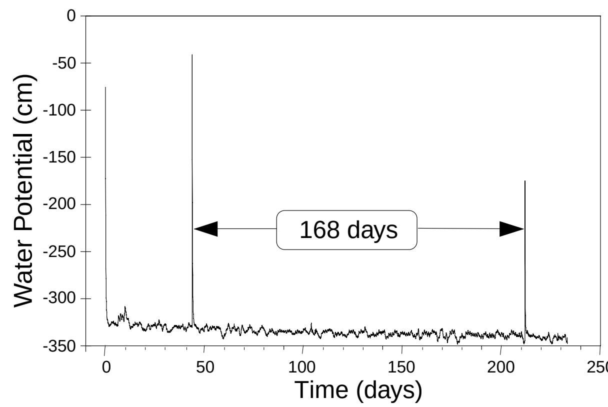

Fig. 6. Borehole tensiometer results during a 233-day test with a 168-day period without purging.

term test was carried out in which a tensiometer equipped with an electronic pressure transducer was placed at the bottom of a 6-m borehole, and the tension values were recorded over a 233-day time period. The results of this test are shown in Figures 5 and 6. Figure 5 shows that due to the limited contact between the porous cup and loam at the bottom of the borehole, approximately 24 hours was required for the tension values to reach equilibrium with the soil water tension. Figure 6 shows the data obtained over the 233-day long-term evaluation test. The sharp rises in soil water potential that occurred on 0, 44, and 212 days into the test correspond to times at which the tensiometer was refilled. Each refilling required between 10 and 20 mL of water. The downward trend in water potential indicated on Figure 6 was fitted with a linear regression line over the 168-day period between refilling, and it indicated that the water potential was declining at a rate of 0.051 ±0.001 cm/day. Day zero of the long term test was February 21, 1995 and the last date for which data are shown is October 12, 1995. The observed downward trend could be due to either evapotranspiration or deep drainage losses or both. The small fluctuations in water potential about the long-term trend indicate that a noise level of approximately ±10 cm of water corresponds to barometric fluctuations and temperature effects on the data logger.

Considering the tension values were obtained at a field site with surface temperature variations between -7 to over 90°F during winter as well as summer, at depths well beyond the range of conventional tensiometers, and the tension values are in the high tension range where conventional tensiometers tend to behave erratically, the results were considered encouraging.

The portable tensiometer can be used for both reconnaissance measurements or for long-term monitoring in wells open at the bottom at depths previously not possible. The portable tensiometer can be used during drilling of boreholes to obtain measurements at specific depths to allow planning for placement of instrumentation. Portable tensiometers can be used as a survey instrument to measure soil water potential at the bottom of boreholes at any depth. The low cost of the portable tensiometer allows many instruments to be placed in multiple boreholes. The portable tensiometer with a pressure transducer/data logger allows continuous measurements for extended times. Soil water potential changes over extended periods of time such as the passing of a wetting front or the formation of perched water can be monitored at depth.

CONCLUSIONS

A retrievable tensiometer for use in reconnaissance surveys of subsurface soil water conditions was evaluated. Operating the tensiometer by lowering it to the bottom of a borehole required a 24-hour response time at low tensions due to the restricted contact between soil and the porous cup. The response time increased with decreasing soil water potential. The portable tensiometer can be retrieved to land surface from deep boreholes without significantly affecting the pressure in the instrument.

It was found that placing the entire tensiometer at the bottom of the borehole increased the length of time between purging events to remove entrapped gases and reduced the diurnal fluctuations seen in tensiometer values obtained where the pressure transducer was maintained at land surface. Nearly continuous tension values were obtained for a period of 233 days at a depth of 6 m. Thus, tension readings at depths applicable to managing landfills are now attainable. The portable tensiometer can be used to obtain single measurements or collect continuous measurements over long time periods with little maintenance of the instrument.

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